Explanation of discrepancies among satellite observations of the aerosol indirect effects

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[1] Satellite-based remote sensing instruments for measuring the aerosol indirect effect (IE = $-d \ln r_e/d \ln \tau_a$ where r_e is the cloud drop effective radius and τ_a is the aerosol optical depth) show large disparities in the magnitude of the effect for similar regions of the globe. Over the oceans, the Advanced Very High Resolution Radiometer (AVHRR) measures an indirect effect twice that measured by the POLarization and Directionality of the Earth Reflectances (POLDER) (0.17 vs. 0.085). We address possible reasons for these disparities. It is argued that AVHRR misses the optically thin and broken clouds, especially over land, while POLDER misses clouds with variable top heights in its field of view. POLDER is also biased to thinner, less turbulent clouds. The sensitivity of the indirect effect to cloud turbulence therefore biases POLDER to lower values. POLDER measures an indirect effect over the ocean that is about twice that over the land (0.085 vs. 0.04). By considering factors such as dynamics, variability in cloud liquid water path, decoupling of the boundary layer, and the effect of salt particles, we argue that this could be an artifact, and that the indirect effect on cloud microstructure may be stronger over land than over the ocean. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 1630 Global Change: Impact phenomena; 1640 Global Change: Remote sensing. **Citation:** Rosenfeld, D., and G. Feingold, Explanation of discrepancies among satellite observations of the aerosol indirect effects, *Geophys. Res. Lett.*, *30*(14), 1776, doi:10.1029/2003GL017684, 2003.

1. Introduction

[2] Aerosols increase cloud albedo because of their activity as cloud condensation nuclei (CCN). Larger concentrations of CCN increase the cloud droplet concentrations, reduce the cloud drop size, and increase the cloud albedo, cloud water being equal [*Twomey*, 1977]. This aerosol indirect effect on cloud albedo has a large cooling effect on the climate system that is estimated to be between 0 and -2 Wm^{-2} [*IPCC*, 2001]. Narrowing this huge uncertainty is an outstanding issue, which has been approached by relating satellite observed cloud properties and aerosols to each other. One way of quantifying this is with IE = $-d \ln r_e/d \ln \tau_a$, [e.g., *Feingold et al.*, 2001] where r_e is the cloud drop effective radius and τ_a is the aerosol optical depth or proxy, at fixed liquid water path. This paper addresses a specific aspect of the measurement of the aerosol indirect effect, namely the fact that various satellite remote-sensing instruments measure this effect in different ways. This may result in biases in estimates of the indirect effect, which at the very least should be taken into account when interpreting results.

2. Discrepancies in Satellite Estimates of the Aerosol Indirect Effect

[3] Cloud drop sizes are usually retrieved using satellite radiometers such as the Advanced Very High Resolution Radiometer (AVHRR) and more recently Moderate Resolution Imaging Spectroradiometer (MODIS). The measurement principle is based on the relation between reflectance from the surface of the cloud drops and absorption within the cloud drop volume, which yields the effective radius r_e of cloud drops near cloud top. The retrieved r_e is sensitive to the absolute value of cloud reflectance. Therefore AVHRR measurements of r_e are disrupted by partially filled pixels and are also affected by the Earth's surface reflectance for clouds with visible optical depth $< \sim 10$. In such cases r_e can be retrieved only when taking into consideration the Earth's surface reflectance, which can be known with sufficient accuracy only over the oceans.

[4] The POLarization and Directionality of the Earth Reflectances (POLDER) instrument [*Deschamps et al.*, 1994] measures cloud top drop size based on the angular distance between the rings of the glory and cloud bows, which are detectable due to their distinct polarization against the non-polarized background. The glory, which is caused by the oscillations of the phase functions of the individual drops near a scattering angle of 180°, fades away as the drop size distribution broadens and the rings at different angles caused by the drops of different sizes interfere and cancel one another. Therefore, the POLDER-retrieved r_e is heavily biased towards clouds with a narrow drop size distribution, whereas clouds with very broad drop size distributions go undetected [*Bréon and Goloub*, 1998]. Because POLDER uses the polarization signal, the Earth's surface reflectance does not affect the measurement at all, so that very thin and broken clouds can be measured equally well over both land and sea surfaces.

[5] The dynamical and morphological structure of clouds also strongly influences the manner in which the two instruments retrieve drop size. Most droplets form in convective updrafts just above cloud base and continue growing with height at a rate proportional to $H^{1/3}$, where H is the distance above cloud base. The power of 1/3 is for

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the case of pure diffusional droplet growth. The power is >1/3 in the case that coalescence occurs [*Rosenfeld and Lensky*, 1998]. Therefore, a convective field of clouds that typically has highly variable cloud top height and H, has a similarly variable field of cloud top r_e. While the glory may be clearly visible when flying low above the tops of individual cloud elements, it can be completely lost from the height of satellite orbit, where the angular field of view of the glory and cloud bows encompasses an area with a cross section of several hundred km. When this large area comprises convective clouds with highly variable H and hence cloud top r_e, POLDER loses its ability to retrieve even the area-average value of r_e. This effect is illustrated in Figure 3 of *Bréon and Goloub* [1998]. In the case of mixed convective and layer clouds, the POLDER detected r_e would be derived from the layer clouds, whereas the signal from the convective elements would be lost. This is clearly visible in Figure 1, even from the modest height of about 10 km, from a cruising passenger aircraft.

[6] Based on the above, POLDER measures more broken and thin layer clouds than AVHRR, especially over land. At the same time, POLDER measures far fewer convective clouds than AVHRR, both over sea and over land. This paper will show that these differences are evident in the retrieved IE values. We will argue that both the different measuring principles of r_e by the POLDER and AVHRR, and the biases to different cloud types, translate to different estimates of the aerosol indirect effect.

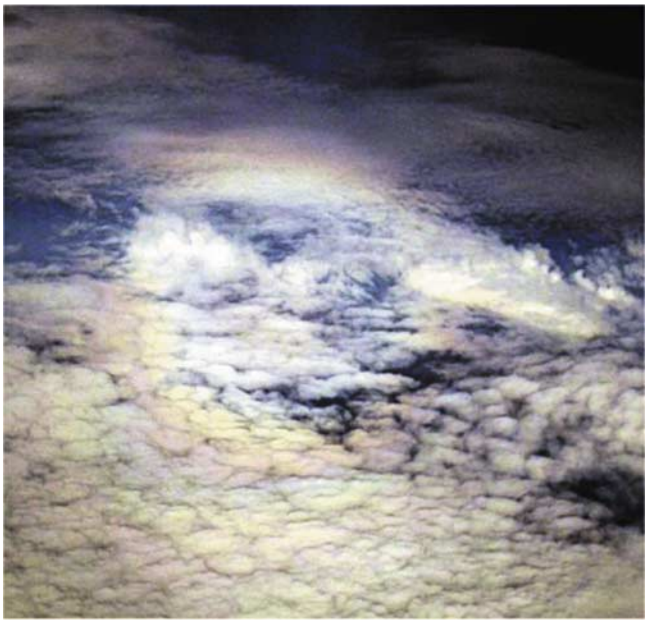

Figure 1. Glory reflected from layer clouds, but not from the underlying convective clouds in the marine boundary layer. Note that the glory is most pronounced in the thinnest clouds at the top of the picture. The convective clouds appear in a left-right orientation slightly above the center of the glory.

2.1. AVHRR vs. POLDER Over the Oceans

[7] *Nakajima et al.* [2001] used the AVHRR data to show that, globally, over the oceans, drop number N_d is proportional to aerosol number $N_a^{0.50}$, which can be shown [*Feingold et al.*, 2001] to be equivalent to IE = 0.5/3 = 0.17. The POLDER based IE was calculated as 0.085 and 0.04 over ocean and land, respectively [*Bréon et al.*, 2002]. The factor of 2 (0.17/0.085) between AVHRR and POLDER over the ocean should be viewed in the light of a number of factors:

2.1.1. Dynamics

[8] The aerosol indirect effect is greater when cloud droplet size is more sensitive to the aerosol amount. Stronger updrafts result in higher supersaturations near cloud base that activate a larger fraction of the aerosols into cloud droplets. *Leaitch et al.* [1996] have shown that the dependence of N_d on N_a in boundary layer clouds becomes stronger and better defined with increasing standard deviation of the updraft velocity, σ_w. The σ_w is a more reliable measure of vertical motions than the absolute values of the updrafts. The larger sensitivity of clouds to aerosols at greater updrafts comes from the fact that the largest aerosols activate at low updrafts and very small supersaturations, but the smaller aerosols require increasingly larger updrafts. This means greater IE for clouds with larger updrafts, or σ_w. This relation has been quantified recently over a continental site by *Feingold et al.* [2003] who showed that IE increases strongly with σ_w. It follows that the IE of thin layer clouds with weak vertical motions tend to be much smaller than the IE for the more convective clouds with their stronger updrafts. Therefore POLDER's bias to shallow, broken clouds implies a bias to clouds with lower turbulence, and lower IE. This can at least partially explain the disparity between AVHRR and POLDER measurements of IE over the ocean.

2.1.2. Liquid Water Path

[9] The shallower clouds favored by POLDER have lower LWP than their more convective, thicker counterparts favored by AVHRR. Unfortunately, neither the *Nakajima et al.* [2001] data, nor the *Bréon et al.* [2002] data are stratified by LWP. This introduces a potentially large source of uncertainty in the derived IE [*Schwartz et al.*, 2002; *Feingold et al.*, 2003]. Given that the indirect effect can be more readily detected at low LWP [*Platnick and Twomey*, 1994], this might indicate a higher IE in the POLDER data. The fact that this is not the case suggests that factors such as cloud turbulence may be even more important.

2.2. POLDER Over Land vs. Polder Over the Ocean

[10] *Bréon et al.* [2002] showed that the POLDER-derived IE over land is 0.04 compared to 0.085 over the oceans, for the same range of aerosol loading. Considering the bias of POLDER to certain conditions, we attempt to understand whether this difference is a real one. This is done from the point of view of (a) land/ocean differences and how they might change IE in reality, and (b) how these differences are observed by POLDER. Because the range of aerosol loading is the same for both land and ocean, one might consider the aerosol over the ocean as being primarily from a continental source, with the addition of a local marine aerosol background. Atmospheric processing during transport might affect this assumption but it is not obvious how.

[11] Beginning with the *expected* differences in IE, we consider the following factors:

[12] (i) Continental regions are generally more convective than oceans [e.g., *Williams and Stanfill*, 2002], and in

light of the previous discussion, IE is expected to be smaller over the ocean;

[13] (ii) Large salt particles that exist over the oceans are fairly effective at reducing cloud supersaturation [*Ghan et al.*, 1998] and therefore suppress activation of some of the CCN. This would tend to decrease IE over the oceans. This effect is most marked at low updraft velocities and polluted conditions where it can lead to ~25% reduction in the concentration of activated droplets.

[14] (iii) The added salt particles over the oceans contribute to enhanced drop coalescence [e.g., *Woodcock*, 1953; *Rosenfeld et al.*, 2002] compared to clouds with the same continental aerosols over land. If one considers the same aerosol concentration and cloud base updraft, the enhanced coalescence increases the drop size in the maritime clouds. The effect is more marked at higher aerosol concentrations, since under clean conditions coalescence is active anyhow. This results in a lower IE over the oceans, especially for convective clouds.

[15] All of these three factors would imply a larger IE over land, i.e., the reverse of what POLDER observes. We therefore evaluate how the POLDER measurement biases for the various cloud types would impact the POLDER-measured IE.

[16] (i) The relationship is less reliable over land because of the larger uncertainty in the aerosol index data there. A greater variance of aerosol index for a given r_e should decrease the slope. However, the error bars in these relations are smaller over land than over ocean, as evident in Figure 3 of *Bréon et al.* [2002]. Therefore, this is not a likely explanation of the different slopes over land and ocean.

[17] (ii) Over land, the thin and/or broken clouds, which dominate the POLDER signal, often occur in stratified conditions that are decoupled from the boundary layer, where the path-integrated aerosol that is used as an indicator of the aerosol effect on the clouds may have little relevance to the aerosol affecting the cloud. This is likely to introduce variability in the indirect effect response and result in smaller IE. This is indeed what POLDER observes;

[18] (iii) The addition of salt particles over the ocean enhances drop coalescence, resulting in broader size distributions. Coalescence broadening tends to obscure the glory and weaken the POLDER- observed IE over the oceans, mainly in convective clouds where coalescence is more active. The fact that a larger IE is observed by POLDER over the oceans implies that other factors dominate this effect, and/or that POLDER misses most of the clouds in which this process occurs because of the variability of the cloud top height and r_e in the POLDER field of view.

[19] Based on the above, it is difficult to be sure of the real difference in IE between land and ocean. There are at least some factors that suggest that, contrary to the POLDER measurements, the IE might even be larger over land. The lack of supporting observations of aerosol size distribution/composition, turbulence, and LWP relegates this to an hypothesis. Regardless, this hypothesis pertains to convective clouds, to which the POLDER is practically blind. The hypothesis has little relevance to the thin layer clouds that produce the bulk of the POLDER signal. Therefore, the remaining likely explanation for the land/ocean difference in the POLDER-retrieved IE comes from the fact that POLDER measures the aerosol index differently over land and ocean. A large systematic difference in the conversion of the measured signals into aerosol index of the same physical meaning might explain the differences in the IE slopes over land and ocean, in spite of the observed continuity of the aerosol index at the coastal boundaries that was indicated by *Bréon et al.* [2002].

3. Conclusions

[20] The differences between the measurement principles of POLDER retrieved r_e and the AVHRR-retrieved r_e bias the POLDER measurements to clouds that possess a much smaller aerosol indirect effect than those measured by the AVHRR or MODIS for the same scenes. It has been shown to vary by a factor of two over the global oceans, with the POLDER obtained IE of 0.085 [*Bréon et al.*, 2002] and AVHRR IE of 0.17 [*Nakajima et al.*, 2001]. It is suggested that this difference is closely tied to the types of clouds measured by each instrument. AVHRR favors deeper clouds with stronger updrafts whereas POLDER favors thinner, less-turbulent clouds. The importance of cloud turbulence in determining the aerosol indirect effect has been documented through in-situ measurements, surface-based remote sensing, and modeling.

[21] The dynamical differences between clouds feeding from the land and ocean boundary layers, i.e., cloud base updrafts being more than double over land than over ocean, should induce an enhanced sensitivity of IE in continental clouds compared to maritime clouds. However, the POLDER retrieved IE = 0.085 over ocean is double the IE = 0.04 over land [*Bréon et al.*, 2002]. This apparent contradiction could be potentially explained if over land the POLDER misses most of the convective clouds occurring in the boundary layer, and detects the r_e mainly from shallow, weakly turbulent layer clouds that are often decoupled from the boundary layer and its aerosols. It could also be explained by different physical meaning of the aerosol index over land and ocean. An analysis of various factors suggests that the real (in contrast to the measured) aerosol indirect effect on cloud microstructure may even be higher over land than over the ocean.

[22] Based on the above, we suggest that caution be exercised when using the POLDER-retrieved aerosol indirect effect on clouds [*Bréon et al.*, 2002] for estimating the global IE, as done, for instance, by *Lohmann and Lesins* [2002]. A global measure can be obtained more reliably by leveraging the advantages of each data set and merging data sets from each instrument. These could be weighted by the frequency of occurrence of the cloud types to which these two methods are sensitive. It is also suggested that to remove ambiguity in the IE measurement, effort should be put into simultaneous and independent measurement of liquid water path.

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